Nannofossil palaeoecology of the Upper Maastrichtian chalk, Danish Central Graben

M-10X (Dan Field), E-5X (Tyra SE Field)

Emma Sheldon



GEOLOGICAL SURVEY OF DENMARK AND GREENLAND MINISTRY OF THE ENVIRONMENT

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Abstract

The nannofossil assemblages in chalk cores from the E-5X and M10-X wells were examined in order to establish whether they can be used to reconstruct palaeoenvironmental conditions in the Late Maastrichtian.

Generally, the 'boreal' nannofossil assemblages in both wells demonstrate oligotrophic cold water conditions. Closer investigation reveals subtle changes in water depth (a regressive period through the Late Maastrichtian followed by a deepening in the latest Maastrichtian), temperature fluctuations and possible nutrient fluxes.

The study includes a detailed section of the M-10X well that has been investigated at high resolution, in order to assess whether laminated/bioturbated bedding cycles reveal any palaeoecological pattern.

Introduction

An increased understanding of pelagic carbonate productivity, sedimentology and stratigraphy will be necessary for future exploration, production and development of hydrocarbon fields in the Danish North Sea. The integration of palaeontology with stable isotopes and sedimentology in this report allows the recognition of climatic, oceanographic and relative sea-level fluctuations recorded in the Upper Maastrichtian chalks.

The aim of this report is to use nannofossils from the E-5X and M-10X wells from the Tyra SE and Dan Fields respectively (Figure 1), as a tool in order to attempt to unravel some of the small-scale palaeoecological changes that took place in the Late Maastrichtian in the Danish North Sea.

It is important to note that observations and suggestions are often hypothetical as few, if any, of the Maastrichtian nannofossil species have living relatives. Living coccolithophores are most diverse at low latitudinal regions, though flourish between 70°N and 70°S, preferably in warm, oligotrophic, mid-ocean environments (Bown & Young 1998). It is assumed that fossil assemblages tolerated similar conditions to extant nannoplankton and it is upon this assumption that this report is based.

Most coccolithophores (with a few exceptions) thrive in the photic zone of the water column which varies from around 200 m in the tropics and decreases polewards (Brasier 1992). Therefore changes in the environment, i.e. changes in temperature, nutrients and to a lesser extent salinity, directly affect the organisms living close to the sea surface. Thus; water depth and distance from the shore affects nannoplankton assemblages, with some groups preferring oceanic settings while other groups thrive close to the shore. Oceanic assemblages fluctuate as a result of changing nutrient levels due to upwelling and deep water circulation. In contrast, in relatively shallow regions, shelf taxa react to changes in nutrient input from continental runoff (Lees 2002).

In addition, nannoplankton is also influenced by latitude (temperature). In the northern hemisphere, for example, assemblages are often referred to the 'boreal' or 'tethyan' realm, depending on their palaeolatitudinal habitat (Burnett 1998).

This study is largely based on observations of nannofloral assemblage composition (Figures 2, 3 and 4), in some cases supplemented by sedimentological, palynological and foraminiferal data (Ineson 2004, this study; Schiøler 2004, this study; Rasmussen & Lassen 2004, this study). An integrated palaeoecological resumé using observations from the palynological, micropalaeontological, nannopalaeontological, carbon isotope and sedimentological studies is presented in Ineson *et al.* (2004a, this study).

Geological Setting

The fine-grained Maastrichtian chalks of Denmark comprise coccolith and foraminiferarich cool water carbonates deposited in water depths of up to several hundred metres (Surlyk & Håkansson 1999). The thick succession of chalk in the Danish Basin includes up to 700m of chalk deposited in the Maastrichtian (Stenested 1972).

Local sea-floor topography in the Maastrichtian was created by local tectonic inversion, in addition to diapirism of the underlying Zechstein salt (Bramwell *et al.* 1999). The cool water pelagic chalks were deposited at a palaeolatitude of approximately 45°N (Smith *et al.* 1994), therefore the nannofossil assemblages in this study reflect deposition at a relatively high palaeolatitude.

Scholle (1974) suggested that deposition occurred at depths below the euphotic zone which rarely extends below 100 m (Thurman 1990). At this time, the studied area was distal to the coastline, approximately 400 km (Surlyk *et al.* 2003), hence terrigenous input was minimal and the chalk was mineralogically pure, comprising almost entirely coccolith mudstone.

Certain levels of the Maastrichtian chalk in the Danish Central Graben reveal a cyclicity comprising bioturbated beds of low porosity alternating with high porosity laminated chalk (Surlyk *et al.* 2003). These cyclic beds are tens of centimetres thick, with the laminated chalk forming approximately a third of the total chalk in the cyclic interval, while bioturbated chalk (and minor conglomerates and massive chalks) makes up the remainder (Damholt & Surlyk 2004). The bioturbated intervals are thought to have been deposited in periods when the sea-floor was well-oxygenated allowing burrowing organisms to homogenise the sediments, while the lamination is thought to have been preserved due to anoxia on the sea floor (Damholt & Surlyk 2004). The latter authors interpret the lamination to reflect the alteration of mm thick chalk turbidites and hemipelagites of similar thickness. The bioturbated and laminated beds can often be traced over large areas (Scholle *et al.* 1998) and this continuity supports the proposal that the cyclicity is linked to the 20,000 year precession cycle within the Milankovitch band.

Method

Core chips were taken from the Upper Maastrichtian and Lower Danian chalk from the E-5X and M10X wells (Figure 1).

62 samples were taken from E-5X and 104 from M-10X (Appendix 1). Sample spacing was approximately 3 feet in the uniform chalk. Closer sample spacing (every 5 to 6 inches) was undertaken at critical horizons, namely the Cretaceous/Tertiary (K/T) boundary and the 6611.58^{-6619.41⁻} interval of M-10X where small-scale laminated/bioturbated cycles were examined (Ineson *et al.* 2004b, this study).

Nannofossil smear slides were prepared using the simple smear slide technique described in Bown and Young (1998). That is: a small amount of chalk was scraped from a freshly broken surface and placed on a glass slide and a drop of water added to make a sediment suspension. The suspension was smeared back and forth over the slide until a uniform rippled effect was obtained and the slide was quickly dried. A couple of drops of Norland Optical Adhesive© were added to a coverslip and this was placed face down on the glass slide. The slide was then left to cure under UV light (sunlight) for 24 hours before analysis.

As the core was taken from major hydrocarbon reservoir levels, core chips were often still saturated in oil when they were processed. As smear slides are prepared using water, 'clumping' was often a minor problem. This occurs where the mixture of oil and water prevents the chalk from disaggregating. In order to prevent this, a mild detergent (washing-up liquid) can be added to the suspension.

The slides were examined using a Leitz Labrolux 8 light microscope. Simple relative abundance counting (Bown & Young 1998) was utilised in this study, i.e. a minimum of 300 specimens were counted (the amount generally regarded as statistically valid) from each slide in order that the presence of rare taxa be recorded. To facilitate palaeoecological analysis, percentage abundances were applied in this report instead of total abundances (see Figures 2, 3 & 4). Graphically, this allows a more direct comparison between palaeoenvironmentally significant groups. The chalk succession from both wells in this study has been tentatively divided into palaeoecological units; each of these is described in this report and can be seen on Figures 2 & 3. The units are correlated between the wells, with correlable events marked on Figures 2 & 3 by red arrows.

Preservation

As has been noted in the nannofossil biostratigraphy section (Sheldon 2004, this study), diagenetic overgrowth is a problem that has to be taken into account when processing and analysing samples, especially when carrying out palaeoecological analyses. In the present nannofossil study, it was noted that the chalk in the M-10X well in particular suffered calcite overgrowth. In some cases (as might be expected, around the Upper Maastrichtian hardground), the overgrowth prevented certain nannofossils from being identified to species level. In comparison, nannofossil assemblages from the E-5X well were extremely

well preserved, with even the most delicate forms remaining in pristine condition. (Surprisingly, this is not in agreement with the foraminifera study from this well (Lassen & Rasmussen 2004, this study)).

For further discussion on the possible causes of differential preservation, refer to Sheldon (2004, this report).



Fig. 1. Danish oil and gas fields (Figure taken from 'Oil and Gas Production in Denmark 2003'; the Danish Energy Authority).

Previous work

The biostratigraphic zonation schemes referred to in this study are the 'UC' scheme of Burnett (1998) and that of 'Network Stratigraphic' from the report 'A Joint Chalk Stratigraphic Framework' (Fritsen 1999).

Only few nannoplankton palaeoecological studies have been carried out on the Upper Maastrichtian and a large amount of literature concerning this time period concentrates on high southern latitudes (Lees 2002). Worsley & Martini (1970) first recognised the significance of certain nannofossil species with latitudinal preferences, when they described *N. frequens* as a boreal Late Maastrichtian marker, that became rarer towards the equator. Thierstein (1976) described the palaeoecological preferences of species apparently endemic to the Indian Ocean (many of these species are now known to be found in the northern high latitudes). He went on to describe global nannofossil palaeoecological patterns from the Upper Campanian–Danian (Thierstein 1981). Locally, Perch-Nielsen (1979) described nannofloras from the Cretaceous/Tertiary boundary in Denmark, along with the palaeoenvironmental significance of the hardground level of the Southern Norwegian and Danish North Sea in his Upper Cretaceous biostratigraphy study. Bergen & Sikora (1998) discussed the evidence for Late Cretaceous warming in the North Sea.

During the Cretaceous as a whole, there appears to have been a relatively large amount of research into nannofossils as indicators of high productivity. Eshet *et al.* (1992) and Eshet & Almogi-Labin (1996), discussed the nannofossils indicative of palaeoproductivity in the Upper Cretaceous and at the K/T level in Israel. Gardin (2002) described nannofossil assemblages from one million years across the K/T boundary in Tunisia while Girgis (1989) described the possible palaeoecological significance of morphometric trends in *A. cymbiformis* from Egypt. However, these authors described palaeoecological trends in nannofossils from 'tethyan' regions, and although some of the same species occur in the 'boreal' realm, palaeoecological patterns are expected to differ between these realms (Girgis 1989). Nannofossils as palaeoproductivity indicators were also described by Watkins (1989) and Erba (1992) from the middle Cretaceous. The genera described by these authors as palaeoproductivity indicators are inferred in this study to represent the same signals, as though by the Late Maastrichtian, different species had evolved.

Watkins (1989) focusses particular attention on rhythmic bedding constructed from limestone and marly cycles. This is particularly relevant in the present study where a cycle of laminated/bioturbated chalk is analysed. Pospichal & Wise (1990) described near-shore nannofloras from the southern hemisphere high latitudes which can, to some extent be compared to those of the northern hemisphere high latitudes. The most recent comprehensive study on the palaeoecology of nannofossils was that of Lees (2002) Although this study was carried out on material from the Indian Ocean and the southern hemisphere, comparison of floras from the 'boreal' realms of both hemispheres can be made.

Palaeoecology of E-5X using nannofossils

In general, the nannofloral assemblages in E-5X (Figure 2) demonstrate a fairly stable, oligotrophic, cool (high latitude), relatively shallow water environment. It should be noted that 'shallow water' here and throughout the report, reflects a shelfal position rather than an oceanic setting. The stability of the environment is reflected by the species richness of the samples. The species richness is around 35 and is fairly constant throughout the well, apart from at the hardground level at the K/T boundary. Slight deviations from the stable setting are illustrated by fluctuations in the nannoplankton assemblages as discussed below, with different species becoming more or less dominant depending on changing palaeoenvironmental criteria.

The cold, shelfal environment is reflected in particular by high numbers of taxa thought to have preferred these conditions. Lucianorhabdus cayeuxii and Kamptnerius magnificus are thought to be indicative of marginal conditions at high latitudes (Roth 1973; Thierstein 1976; Perch-Nielsen 1979; Pospichal & Wise 1990), while Arkhangelskiella cymbiformis is also a near-shore indicator (Perch-Nielsen 1979), Prediscosphaera stoveri and Micula decussata are also cold water taxa (Thierstein 1976; Pospichal 1996), while M. decussata is also thought to be an indicator of deeper water (J. Lees and K. Cooper, pers. comm.) conditions and is also a solution resistant taxon (Thierstein 1976, 1981). Other high latitude indicators used in this report include Ahmuellerella octoradiata (Thierstein 1976; Siesser 1982) and Nephrolithus frequens (Worsley & Martini 1970; Thierstein 1976; Perch-Nieslen 1979). Though the surface waters were thought to have been cool in this part of the Maastrichtian, possible minor warming events can be evidenced by slight increases in Watznaueria barnesae, a taxon affected by warmer temperatures (Watkins 1992; Lees 2002) often associated with the low latitudes (Shafik 1978). Also possibly related to temperature is A. cymbiformis; abundances fall when surface waters become cooler (Girgis 1989). Primary productivity fluctuations are also represented by changes in nannoplankton populations. The shift from an oligotrophic to a eutrophic environment due to increases in nutrients are seen in assemblages with low species richness, dominated by Biscutum spp., Discorhabdus spp., Chiastozygus spp. and Zeugrhabdotus spp. (Watkins 1989; Erba 1992; K. Cooper pers. comm.). Thoracosphaera spp., a calcareous dinoflagellate cyst that reacted to perturbations in surface water conditions especially where nannoplankton were adversely effected, is seen in 'bloom assemblages' following the K/T boundary (Perch-Nielsen 1985b; Mortimer 1987; Eshet et al. 1992). Conversely, low primary productivity, as seen throughout most of this well, is represented by high abundance and diversity assemblages with Prediscosphaera cretacea and Eiffelithus turriseiffelii (Eshet & Almogi-Labin 1996).

Unit 1

6975.17'-6859.83'

Definition

Nannofloral assemblages from the main part of the E-5X well from the bottom of the core to around 6859.83'demonstrate a stable, oligotrophic, cool water palaeoenvironment. The nannofossil species used in this report to indicate palaeoenvironmental change show minor fluctuations throughout this interval, but these are not thought to represent any major palaeoecological shifts. These small-scale fluctuations are described below.

Correlation

The overall trends in nannofossil assemblages suggesting a cool, stable palaeoenvironment seen in the E-5X well (Figure 2) are also recognised in the M-10X well (Figure 3). In E-5X, the present unit is subdivided into unit 1B and unit 1C only. Due to a larger section of core being analysed in M-10X, unit 1 is subdivided into units IA, 1B and 1C in that well.

Unit 1B

6975.17′-6920.75′

Definition

Nannofossil assemblages appear to suggest an overall deepening from the bottom to close to the top of the unit. This is represented by a general increase in *M. decussata* accompanied by an overall decrease in *L. cayeuxii*. Relatively high abundances of nannofossils indicative of high productivity also characterise this unit. However these abundances are only relative, the general setting is one of low productivity.

Palaeoenvironmental trends

In this interval in E-5X, the diverse nannofloral assemblage contains high numbers of *L. cayeuxii* suggesting cool water marginal conditions. Cold surface water temperatures are also suggested by consistently high numbers of *P. stoveri*, increasing *K. magnificus* (peaking at 6920.75') and very low numbers of *W. barnesae* (a warm water indicator) and fairly consistent *A. cymbiformis*. *N. frequens* (a cool water, high latitude taxon) is present throughout the well. The abundance of *M. decussata* increases stratigraphically upwards suggesting a possible relative rise in sea level towards the top of the interval. At the same

time as the overall increase in *M. decussata*, *L. cayeuxii* slowly decreases to 6926,17', also suggesting a possible relative rise in sea level.

It might be expected that *K. magnificus* would demonstrate similar trends to *L. cayeuxii*, as it is also an indicator of cool shallow water environments. In fact, *K. magnificus* is present in fairly low numbers in the bottom part of the interval where *L. cayeuxii* is abundant. This could be due to the fact that slightly different temperatures and water depths are preferred by each species, or possibly that these species are in direct competition.

The indicators of high productivity are fairly common throughout the interval, and peak at 6956.83', 6948.92', 6935.83' and 6923.83'. These peaks are perhaps related to weak nutrient fluxes causing mildly eutrophic conditions in the surface waters.

Correlation

Several trends seen within this unit can be correlated with similar patterns in the M-10X well. At 6960.17' a minor peak in *P. stoveri* accompanied by a decrease in abundance of *A. cymbiformis* could indicate a local cooling event. This is followed at 6956.83' by a peak in the high productivity indicators, particularly *P. fibuliformis*. A large peak in *P. stoveri* at 6938.33' can also be seen in M-10X. Towards the top of the unit, a productivity high (marked in particular by an increase in *Ch. amphipons*) coincides with a small peak in *M. decussata*. At the very top of the interval is an influx of *L. cayeuxii*, which can also be correlated with M-10X.

Unit 1C

6920.75'-6859.83'

Definition

Using nannofossil assemblage patterns, this unit represents an overall relative shallowing as seen by the decrease in abundance of *M. decussata* and the overall increase in *L. cayeuxii*. It is difficult to pin-point the peak regression, as within the general shallowing pattern, smaller-scale fluctuations occur perhaps suggesting minor superimposed relative sea-level changes. Towards the top of this unit, the patterns shown by *A. cymbiformis*, *L. cayeuxii* and to a lesser extent *M. decussata*, indicate a period of relative shallow water. This is supported by foraminiferal assemblages (Rasmussen & Lassen 2004, this study).

Palaeoenvironmental trends

This interval demonstrates a gradual decrease in the abundance of *M. decussata*, which indicates a relative fall in sea level. The top of this interval is somewhat artificial as there is a sample gap of 12' above 6859.83'. In addition, it is difficult to say whether the minimum abundance of *M. decussata* lies as 6881.41' (the point tentatively chosen as the peak re-

gression in this well using nannofossil abundances) or at 6859.83'. As *M. decussata* decreases in abundance, *L. cayeuxii* (indicative of cool, relatively shallow waters) increases in abundance to the top of this interval, peaking at 6875.33' and again at 6859.83'. This pattern supports the suggestion that relative sea level was falling within this interval with a possible local rise at 6866.25' as seen by another increase in *M. decussata* and supported by Schiøler (2004, this study).

In addition, it was suggested by Perch-Nielsen (1977) that *L. cayeuxii* could be an indicator of facies change. Supporting this, the interval where *L. cayeuxii* markedly increases, 6872.66′–6859.83′ coincides with a major porosity peak based on petrophysical data and with the period of peak regression according to foraminiferal data (Rasmussen & Lassen 2004, this study).

The common occurrence of *L. cayeuxii* also indicates cool waters; this is supported by small increases in *K. magnificus* (also indicating cool, relatively shallow conditions). However, *K. magnificus* remains fairly low in abundance throughout this interval, possibly due to its competition with *L. cayeuxii*.

Within this interval, an acme of *P. stoveri* occurs between 6894.00' and 6863.33', also indicating a cooling of the surface waters. Coincident with the acme of *P. stoveri*, *A. cymbiformis* demonstrate a fall in abundance, followed by an interval where they are particularly low in abundance and then an increase at the same time that *P. stoveri* decreases. This pattern in *A. cymbiformis* also supports a cooling event within this interval followed by a warming as *P. stoveri* decreases. Strangely, this event does not appear in the M-10X well, suggesting that this was only a very local event. *W. barnesae* is present in low numbers throughout most of this interval, though demonstrating small peaks at 6916.33' and 6903.75', possibly indicating slight warmer water incursions at these levels.

As in the previous interval, the indicators of high productivity are fairly common throughout, peaking at around 20% at 6881.41'. Smaller peaks occur at 6919.17', 6903.75' – 6900.75', and 6872.66'. These peaks are inferred to indicate minor influxes of nutrients in the surface waters.

Correlation

Several events or trends seen within this unit in E-5X can be correlated with equivalent trends in the M-10X well (Figure 3). From the bottom of the unit, a peak in *P. stoveri* followed by a small peak in *M. decussata* can also be traced to M-10X. This is followed by a peak in *A. cymbiformis* at 6906.83', which roughly correlates with porosity peak C of Toft *et al.* (1996). A small peak in *L. cayeuxii* at 6889.33' is followed by a large productivity peak (particularly noticeable are high values of *P. fibuliformis*).

6859.83'-6847.83'

sample gap

Unit 2

6847.83'-6824.83'

Definition

This base of this unit marks the onset of changing conditions in both wells. Below this point, the environment had generally been fairly cool and oligotrophic. Using nannofossils, from this point onwards, an overall transgressive pattern is indicated by an upwards increase in abundance in *M. decussata* and low numbers of *L. cayeuxii* and *K. magnificus*, coupled with a warming event from approximately 6847.83' almost to the top of the Cretaceous inferred by the increase in abundance in *W. barnesae*. Conversely, the bottom of this interval also sees the incoming of shelly debris, possibly pointing to a minor shallowing event (Ineson 2004, this study).

Palaeoenvironmental trends

This interval is marked by a slow but steady increase in the abundance of M. decussata (a species possibly indicative of deeper waters) and relatively high numbers of the warm water taxa W. barnesae (peaking at 6824.83'). These two parameters suggest a sea-level rise coinciding with a warming event. It is interesting to note that peaks in the planktonic foraminifera Pseudotextularia elegans occur at 6847.83' and 6833.50' (Rasmussen & Lassen 2004, this study). This 'tethyan' species apparently lived in the lower regions of the photic zone and is thought to indicate slightly deeper and warmer waters. A brief warming event at the end of the Maastrichtian is documented by Huber & Watkins (1992) & Lees (2002). To support this, the cool and relatively shallow water indicators, K. magnificus and L. caveuxii are consistently low in abundance within this interval, but demonstrate a slight decrease stratigraphically upwards. The cold water taxa P. stoveri fall in abundance roughly coinciding with the incoming of W. barnesae, though they show a sharp peak at 6827.92' concurrent with a marked drop in abundance of A. cymbiformis which, until this point had remained fairly stable. This 'event' is only present in one sample and could tentatively represent a short lived influx of cold water. The indicators of high productivity show a weak but fairly stable signal throughout this interval, but peak (most notably Ch. amphipons) at 6830.00'.

Correlation

The general warming pattern seen within this interval in E-5X, indicated by an increase in abundance of *W. barnesae* can be correlated with the same trend in the M-10X well (Figure 3). The peak in abundance of *Ch. amphipons* at 6830.00' towards the top of the 2nd *P. grallator* acme (Schiøler 2004, this report) also appears in the same stratigraphic interval in M-10X. The level at which an influx of shelly debris is recognised can also be traced in M-10X.

Unit 3

6824.83′-6819.17′

Definition

This relatively thin unit is characterised by a large increase to peak values of *M. decussata* coinciding with decreased values in species richness. These two parameters coincide with the Upper Maastrichtian hardground level seen in both wells. In the same interval, several samples comprise nannofossils characteristic only of the Maastrichtian and only of the Danian. These samples are referred to the 'mixed' zone, a biostratigraphically complex interval created by infill of biogenic cavities beneath the top-Maastrichtian hardground surface with Danian sediment.

Palaeoenvironmental trends

Nannofossil assemblages change dramatically in the uppermost part of the Maastrichtian. Assemblages are dominated by M. decussata and A. cymbiformis, whilst there is a reduction in most other species. This is reflected by the fall in species richness from 39 to 26 (Figure 2). Until this point, M. decussata had been used to indicate deeper waters. However, the change in the species richness values that are more or less constant up to this level, indicates that M. decussata cannot be used as a palaeoenvironmental indicator at this level. M. decussata is also known to be a nannofossil species that is resistant to solution (Thierstein 1976, 1981). The hardground at the K/T boundary has been welldocumented (Mortimer 1987; Fritsen 1999; Surlyk et al. 2003) and it is due to early diagenetic processes at this hardground that M. decussata is preferentially preserved. Falls in abundance of K. magnificus and L. cayeuxii (cool, relatively shallow water taxa) could also be attributed to the continuation of the warming event as W. barnesae (a warm water taxa) continues to be present. Similarly, A. cymbiformis (also thought to be associated with warm water, Girgis 1989) remains high in abundance. However, from 6823.33'-6820.00', a fall in abundance of W. barnesae along with an increase in K. magnificus suggests a cooling just before the K/T boundary; this inferred cooling event has also been noted from Stevns Klint on the east coast of Denmark (Hart et al. 2004). Species richness levels recover somewhat (to 38) within the 'mixed' zone. This increase represents the high abundance and diversity assemblages within the interval, represented by both Danian and Maastrichtian nannofossils. The indicators of high productivity remain fairly common in this interval, although less significant than lower in the section. A slight increase in abundance of Thoracosphaera spp. is noted in the top of this unit, the significance of which is discussed below.

Correlation

A slight cooling event is noted just before the 'mixed' zone in both wells. Trends demonstrating a relatively low species richness and high *M. decussata* values indicating a hardground are found in both E-5X and M-10X. Similarly, the 'mixed' zone comprising Maastrichtian and Danian nannofossils is common to both wells. High productivity indicators remain fairly common within this unit.

Unit 4

6819.17'-6809.25'

Definition

This unit comprises a relatively low diversity Danian nannoflora, characterised by a 'bloom' assemblage (see below) of the calcareous dinoflagellate cyst *Thoracosphaera* spp.

Palaeoenvironmental trends

Following species richness levels of around 35 in the Upper Maastrichtian, they fall back to around 14 in the Danian. Coincident with the drop in species richness is the disappearance of most Maastrichtian taxa followed by a 'bloom' in the calcareous dinoflagellate cyst *Thoracosphaera* spp. together with low diversity Danian assemblages. This represents a stressed environment following the stable oligotrophic conditions of the Upper Maastrichtian. The high abundance and diversity assemblages common to the Upper Cretaceous die out and are replaced by the opportunistic *Thoracosphaera* spp. Whether this species is in fact 'blooming' is debatable (Gartner 1996). It is likely that this calcareous dinoflagellate cyst took advantage of the niches left vacant by the Maastrichtian flora. Eventually, *Thoracosphaera* spp. became reduced in numbers as the Danian flora evolved and occupied the photic zone once more. The Danian part of this well will not be discussed further in this study.

Correlation

The dramatic fall in species richness levels and the 'bloom' of *Thoracosphaera* spp. can be seen in both the E-5X and M-10X wells. The high productivity indicators are still present within this interval.



Figure 2: E-5X: Nannofossil (% abundance) distribution chart showing trends of selected species with palaeoenvironmental significance.

Palaeoecology of M-10X using nannofossils

As in the E-5X well, nannofloras in M-10X (Figure 3) demonstrate a fairly stable, oligotrophic, cool (high latitude), shelf environment. The stability of the environment is reflected by the species richness of the samples. The species richness is around 35-38 and is fairly constant throughout the well, apart from at the hardground level at the K/T boundary. Slight deviations from the stable setting are illustrated by fluctuations in the nannoplankton assemblages as discussed below, with different species becoming more or less dominant depending on changing palaeoenvironmental conditions.

Nannofossils thought to be palaeoenvironmentally significant are discussed above in the introduction to the E-5X section.

Unit 1

6655.58'-6483.83'

Definition

As in the E-5X well, nannofloral assemblages from the main part of the M-10X well from the bottom of the core to around 6483.83' record a stable, oligotrophic, cool water palaeoenvironment. The nannofossil species used in this report to indicate palaeoenvironmental change show minor fluctuations throughout this interval, but these are not thought to represent any major palaeoecological shifts. These small-scale fluctuations are described below.

Correlation

The overall trends in nannofossil assemblages suggesting a cool, stable palaeoenvironment seen in the E-5X well are also recognised in the M-10X well. Due to a larger section of core being analysed in M-10X than in E-5X, unit 1 is subdivided into units IA, 1B and 1C. In E-5X, this unit is subdivided into units 1B and 1C only.

Unit 1A

6655.58'-6601.58'

Definition

This unit is defined arbitrarily as it shows similar features to and supplements the overlying unit 1B; it is described here to record the nature of the lowest interval in M-10X as the equivalent section was not cored in the E-5X well. Environmental conditions within this in-

terval appear to have been fairly stable as demonstrated by overall unchanging abundances of *M. decussata*, *K. magnificus* and *L. cayeuxii* and constant, relatively high levels of the nannofossils indicating high productivity. The only deviation from this pattern is seen in the lowermost levels of the interval where a local deepening and a decrease in primary productivity is indicated.

Palaeoenvironmental trends

As noted above, this unit supplements unit 1B and is not defined using distinctive palaeoecological events.

The thin interval from 6655.58'-6648.50' comprises assemblages with low numbers of high productivity indicators, a peak in *P. stoveri* (an indicator of cold water) and a peak in *M. decussata* (an indicator of deeper waters). *K. magnificus* and *L. cayeuxii* (cold, relatively shallow water indicators) show consistant levels as does *A. cymbiformis*. Numbers of *W. barnesae* are relatively high possibly suggesting a minor warming of surface waters relative to further up section. As this thin interval is at the bottom of the studied core, it is not possible to analyse the palaeoenvironmental signature, other than to suggest that surface waters were possibly influenced by a weak warming event at this level and were deep relative to succeeding deposits

In general, however, unit 1A is suggestive of oligotrophic conditions, as apart from a general fall in numbers of *M. decussata*, (pointing to a slight shallowing), nannofloral assemblages are stable. Interpretations from planktonic and benthic foraminifera ratios also support a fairly shallow palaeoenvironment (Rasmussen & Lassen 2004, this study). Apart from at a few points, the consistency in numbers of *L. cayeuxii* and *K. magnificus* (cool, relatively shallow water indicators), P. stoveri (indicative of cold water), A. cymbiformis and the species thought to represent fluctuations in surface water productivity indicate a fairly stable palaeoenvironment.

Enhanced productivity indicators within this interval are overall relatively high. Peaks in the high productivity indicators occur at 6641.00⁻, two within the interval discussed for 'cyclicity', and at 6601.58⁻. These 'peaks' broadly coincide with intervals that demonstrate welldefined lamination (Ineson 2004, this study); the interval studied for cyclicity (6619.41⁻ - 6611.58⁻) is dicussed in detail later in this report (Figure 4).

Unit 1B

6601.58'-6542.58'

Definition

Nannofossil assemblages appear to indicate an overall deepening from the bottom to close to the top of the unit. This is represented by a general increase in *M. decussata* accompanied by an overall decrease in *L. cayeuxii*. An exception to this is noted from 6560.75'- 6548.92'. Relatively high abundances of nannofossils indicative of high productivity also

8.92'. Relatively high abundances of nannofossils indicative of high productivity also characterise this unit, apart from within an interval of apparent cooling/deepening between 6579.83'-6563.41'.

Palaeoenvironmental trends

This bottom of this unit correlates with the base of the equivalent section in E-5X. The nannofossil assemblages broadly speaking, demonstrate oligotrophic, cool water, relatively shallow water conditions with an overall deepening towards the top of the interval as indicated by an increase in *M. decussata* (an indicator of deep water) coinciding with a minor fall in *K. magnificus* (a cool, comparatively shallow water indicator). *L. cayeuxii* (also an indicator of cold, fairly shallow water) generally increases towards the upper half of the interval, and then fluctuates, but opposes the trends shown by *M. decussata*. This suggests a relative sea-level fall around 6582.58′–6571.17′ followed by a relative sea-level rise from 6571.17′–6563.41′. This is supported by micropalaeontological evidence (Rasmussen & Lassen 2004, this study).

From 6571.17'-6548.92' L. cayeuxii shows a marked decrease upwards, while K. magnificus increases in abundance upwards. As both are cool, relatively shallow water species, it might be expected that they should show the same trends. The fact that they do not suggests either that they are in direct competition with each other in this interval or that a factor other than temperature or water depth is influencing the assemblages. M. decussata decrease in abundance too, indicating a relative sea-level fall, this would correlate with increase in K. magnificus if it was related to sea-level change rather than temperature. In addition, W. barnesae (a warm water taxa) is present, but only in consistently low numbers. P. stoveri (a cold water taxa) peaks at 6557.58' for one sample. These parameters seem to suggest that temperature is not a significant factor in this interval.

The abundances of those nannofossils indicative of high productivity, however, show a notable increase towards the top of the level, particularly in *Ch. amphipons* and *P. fibuli-formis*; their highest abundance coincides with lows in *L. cayeuxii* and *M. decussata*. It is also worth noticing a peak in *Biscutum ellipticum* at 6563.41'; this coincides with a small peak in *Discorhabdus ignotus*. *Biscutum* spp. and *Discorhadbus* spp. are thought to follow the same productivity trends as each other, while *Chiastozygus* spp. and *Zeugrhabdotus* spp. (*Zeugrhabdotus* spp. are related to *Placozygus* spp., J. Lees, pers. comm.) tend to react to other productivity parameters, i.e. different nutrients. This may explain the variation observed at this level. The indicators of high productivity are fairly abundant throughout this interval particularly in the lower and upper parts, and peaking (particularly *P. fibuliformis*) at 6582.58'. The upper level with especially high abundances of the high productivity indicators is also associated with a notable increase in *Ch. amphipons*. It may also be noted that the upper level of high productivity coincides with an interval showing well preserved laminated chalk cycles (Ineson 2004, this study).

Correlation

Several trends seen in this well can be correlated with those apparent in the E-5X well (Figure 2). A peak in *P. stoveri* coinciding with a fall in *A. cymbiformis* at 6590,00' suggests a minor cooling event, followed by a peak in the high productivity indicators, particularly *P. fibuliformis* at 6582,58'. A peak in *P. stoveri* is followed by a productivity peak (particularly in *Ch. amphipons*) and at the top of the unit, a peak in *M. decussata* can be correlated with equivalent events in E-5X.

Unit 1C

6542.58′-6483.83′

Definition

Using nannofossil assemblage patterns, this unit is suggestive of an overall relative shallowing as seen by the decrease in abundance of *M. decussata* and the overall increase in *L. cayeuxii*. It is difficult to pin-point the peak regression, as within the general shallowing pattern, minor fluctuations may represent smaller-scale relative sea-level rises and falls. Towards the top of this unit, the patterns shown by *L. cayeuxii*, *K. magnificus* and *M. decussata*, indicate a period of relatively shallow water. This is supported by foraminiferal assemblages (Rasmussen & Lassen 2004, this study).

The lower part of this unit is characterised by high abundances of the high productivity indicators that tend to decrease in abundance towards the top of the unit.

Palaeoenvironmental trends

This unit seems to demonstrate a shallowing upwards, based on the overall trends exhibited by *M. decussata* and *L. cayeuxii. M. decussata* decreases in abundance and *L. cayeuxii* (a marginal and cool water indicator) generally increases to the top of the unit. A peak regression or sea-level lowstand has been inferred (based only on nannofossil evidence) at 6495.50'. From this point to the top of this interval, *M. decussata* remains very low in abundance, and *K. magnificus* remains relatively high in numbers. This also suggests a period of relative low sea-level. The relatively low sea-level stand in this interval is supported by foraminiferal evidence (Rasmussen & Lassen 2004, this study) and sedimentological data (Ineson 2004, this study).

The high productivity indicators, particularly *P. fibuliformis* and *Ch. amphipons* are relatively high in abundance in the lower part of this interval. Coinciding with this is a particularly well laminated composite cyclic interval between 6539.92 ' and 6531.00'. These productivity indicators decrease gradually from around 6511.50' to the top of this unit.

Nannofossils indicative of temperature change, *P. stoveri* (a cold water taxa), *W. barnesae* (a warm water indicator) and *A. cymbiformis*, fluctuate randomley throughout this interval.

This fluctuation is interpreted as representing stable oligotrophic conditions in which temperature changes were not significant.

Correlation

At the bottom of this interval, successive peaks in *L. cayeuxii*, *P. stoveri* and *M. decussata* can be correlated with equivalent events in the E-5X well (Figure 2). These are followed by an increase in *A. cymbiformis* just below the C log marker of Toft *et al.* (1996), also seen in E-5X. A significant peak in *L. cayeuxii* at 6519,41' followed by a peak in the high productivity indicators (particularly *P. fibuliformis*) can also be traced between the two wells.

Unit 2

6483.83'-6446.50'

Definition

This base of this unit marks the onset of changing conditions in both wells. Prior to this point, the environment had generally been fairly cool and oligotrophic. Based on nannofossils, from this point onwards, an overall transgressive pattern is indicated by an upwards increase in abundance of *M. decussata*, low numbers particularly of *K. magnificus*, and a decrease in the upper part of the unit of *L. cayeuxii*. This is coupled with a warming almost to the top of the Cretaceous as inferred by the increase in abundance in *W. barnesae*. In contrast to the indications of deepening in this unit based on the nannoflora, an incoming of shelly debris in the upper half of the unit points towards shallower conditions (Ineson 2004, this study).

Palaeoenvironmental trends

This interval is characterised by the incoming of relatively high abundances of *W. barnesae* (a warm water taxon) indicating warmer surface waters, while *P. stoveri*, an indicator of cold waters, fluctuates throughout the interval. The planktonic foraminifera *Pseudotextularia elegans* peaks in this interval at 6481.00', also supporting a warming of surface waters (Rasmussen & Lassen 2004, this study). From 6449.17'–6441.92' (spanning units 2 & 3) a fall in abundance of *W. barnesae* along with an increase in *K. magnificus* suggests a cooling just before the K/T boundary; this trend has also been noted from Stevns Klint on the east coast of Denmark (Hart *et al.* 2004).

The overall increase in W. barnesae coincides with an overall increase in abundance of M. decussata (a deeper water indicator), low numbers of K. magnificus (a cool, shallow water indicator) and a gradual decrease in L. cayeuxii (also a cool, shallow water species). These parameters point strongly to a rise in sea level throughout this interval. The markedly low numbers of K. magnificus in comparison to abundance levels through the rest of the cored section, suggest that this species is possibly more sensitive to temperature than sea level

in this interval. In the same way, the fact that *L. cayeuxii* for the lower part of this interval, remains relatively abundant, despite falling off towards the top of the interval, suggests that this species might not be quite so sensitive to the palaeoenvironmental conditions in this interval as *K. magnificus*. Between 6460.00' and 6451.83', *L. cayeuxii* fall in abundance while *M. decussata* are particularly common. This indicates an overall deepening at this level. This is supported by palynological analysis (Schiøler 2004, this study). *A. cymbiformis* falls in abundance and rises again, opposing the general pattern of *M. decussata* and therefore also suggesting a rise in sea level.

However, in the interval 6456.75'-6454.33', foraminiferal evidence points to a marked shallowing. Such a relative sea-level fall might be supported by the increase in shelly debris noted from around 6465', in addition to a marly interval that coincides with the foraminiferal excursion. A clay influx may also be interpreted to support a minor sea-level fall, although a climatic cause for increased run-off cannot be ruled out.

The nannofossils indicative of high productivity, remain fairly low in abundance in this unit. However palynological evidence suggests enhanced productivity within the lower part of this interval (Schiøler 2004, this report).

The general nannofloral assemblage patterns suggest a relatively warm interval terminated by a cooling event before the K/T during which relative sea level was rising.

Correlation

This interval sees the incoming of *W. barnesae* in increased numbers indicating a warming that can also be seen in E-5X (Figure 2). Similarly, a cooling event just before the 'mixed' zone can be seen at the same level within E-5X. Increased numbers of *Ch. amphipons*, a high productivity indicator is seen at the top of this interval (within the 2nd *P. grallator* acme, Schiøler 2004, this report) in both wells. The level of increased shelly debris can also be traced in E-5X.

Unit 3

6446.50'-6439.00'

Definition

This relatively thin unit is characterised by a large increase to peak values of *M. decussata* coinciding with slightly decreased values in species richness. These two parameters coincide with the Upper Maastrichtian harground level seen in both wells. In the same interval, several samples comprise nannofossils characteristic only of the Maastrichtian and only of the Danian. These samples are referred to the 'mixed' zone, a biostratigraphically complex interval created by infill of biogenic cavities beneath the top-Maastrichtian hardground surface with Danian sediment.

Palaeoenvironmental trends

Nannofloral assemblages change noticeably in this interval. Assemblages are dominated by *M. decussata* while most other species fall in abundance. This dominance of *M. decussata* is coincidental with a fall in species richness from 40 at 6446.50' to 32 at 6444.83', a low level only locally reached in this well.

Apart from being an indicator of increased water depths, *M. decussata* is known to be a species that is fairly resistant to solution (Thierstein 1976, 1981). The coincidence of a *M. decussata* influx with a fall in species richness suggests that *M. decussata* may not be used solely as a palaeoecological indicator in this interval, but instead could be indicative of early diagenesis associated with hardground development at the end of the Maastrichtian. As previously noted, from 6449.17' to 6441.92' (spanning units 2 & 3), a fall in abundance of *W. barnesae* along with an increase in *K. magnificus* suggests a cooling just before the K/T boundary. This cooling trend has also been noted from Stevns Klint on the east coast of Denmark (Hart *et al.* 2004). This interval also shows a slight increase in the species indicative of high productivity, particularly *Ch. amphipons*. This could be a reaction to the stressed environments in the Late Maastrichtian surface waters, also suggested by an influx of the calcareous dinoflagellate cyst *Thoracosphaera* spp.

Correlation

A slight cooling event is noted just before the 'mixed' zone in both wells. Trends demonstrating a relatively low species richness and high *M. decussata* values indicating hardground development are found in both M-10X and E-5X. Similarly, the 'mixed' zone comprising Maastrichtian and Danian nannofossils is common to both wells. High productivity indicators remain fairly common within this unit.

Unit 4

6439.00'-6433.58'

Definition

This unit comprises a relatively low diversity Danian nannoflora, characterised by a 'bloom' assemblage of the calcareous dinoflagellate cyst *Thoracosphaera* spp.

Palaeoenvironmental trends

Following high species richness levels in the Upper Maastrichtian, they decrease markedly in the Danian. Coincident with the drop in species richness is the disappearance of most Maastrichtian taxa followed by a 'bloom' in the calcareous dinoflagellate cyst *Thoracosphaera* spp. together with low diversity Danian assemblages. This represents a stressed environment following the stable oligotrophic conditions of the Upper Maastrich-

tian. The high abundance and diversity assemblages common to the Upper Cretaceous die out and are replaced by the opportunistic *Thoracosphaera* spp. Whether this species is in fact 'blooming' is debatable (Gartner 1996). It is likely that this calcareous dinoflagellate cyst took advantage of the niches left vacant by the Maastrichtian flora. Eventually, *Thoracosphaera* spp. became reduced in numbers as the Danian flora evolved and occupied the photic zone once more. The Danian part of this well will not be discussed further in this study.

Correlation

The dramatic fall in species richness levels and the 'bloom' of *Thoracosphaera* spp. can be seen in both the E-5X and M-10X wells. The high productivity indicators are still present within this interval.



Figure 3: M-10X: Nannofossil (% abundance) distribution chart showing trends of selected species with palaeoenvironmental significance.

M-10X Cyclicity study

The interval 6619.41'-6611.58' was chosen to conduct a detailed palaeontological, stable isotope and sedimentological study to investigate the origin of small-scale laminated/bioturbated cycles (Figure 4). The cycles comprise alternating, decimetre sized, high porosity laminated and low porosity bioturbated intervals (Scholle et al. 1998). In addition to the highly porous laminated intervals representing the best reservoir levels within the Dan Field (Toft et al. 1996; Scholle et al. 1998), the bedding cycles are thought to represent a possible method of long distance correlation and a tool for the subdivision of chalk hydrocarbon reservoirs in the Central Graben of the North Sea (Surlyk et al. 2003). The more porous, laminated half-cycles comprise alternating pelagically derived laminae and laminae interpreted as being formed by low density turbidity currents (Damholt & Surlyk 2004). The bioturbated, less porous, portions retain no sedimentary structures but are thought to record comparable processes (Damholt & Surlyk 2004). Their complicated internal composition and broad lateral extent suggest these cycles are the result of external forcing (Toft et al. 1996; Scholle et al. 1998; Damholt & Surlyk 2004) in preference to turbidite derivation (Kennedy 1987a & 1987b). The bedding cycles of the Upper Maastrichtian chalk are thought to correspond to the 22.5 ka Milankovitch precession cycles (Stage 1999; Damholt & Surlyk 2004). This study was carried out to test if the rhythmically bedded sediments in this interval exhibited any fluctuations in nannofossil assemblages, in turn determining whether these orbitally forced climatic cycles had any effect on nannoplankton.

21 nannofossil samples spaced at approximately 6" intervals (Appendix I) were examined in this interval (dated as subzone UC20b, Burnett 1998) of the Upper Maastrichtian chalk of M-10X. The cyclic level is referred to palaeoecological unit 1A (herein).

The section was divided up into lithological intervals (see Ineson *et al.* 2004b, this study) as follows (and colour coded on Figure 4).

- I) laminated, trace fossils absent (dark blue)
- II) laminated with local burrows/diffuse lamination (pale blue)
- III) bioturbated, local preservation of lamination (orange)
- IV) bioturbated, lamination absent (yellow)

Scholle *et al.* (1998) suggested that the porous, laminated sediments were deposited relatively rapidly, thus precluding burrowing, but Surlyk & Damholt (2004) re-interpreted the laminated intervals, suggesting that preservation of lamination was the result of periodic anoxic conditons on the seafloor. It was suggested that oxygen levels would have been too low to support infaunal and epifaunal organisms that might mix the sediment, hence lamination was preserved.

When higher levels of oxygen prevailed on the sea floor once more, burrowing resumed destroying the most recently deposited laminae. The bioturbated units are thought to have formed when sediments are mixed by epifauna and infauna, indicating a well-oxygenated

sediment-water interface and uppermost sediment layer and relatively low sedimentation rates.

The nannofossil assemblages are diverse and abundant with a continuous species richness of around 30-33. Overall, this indicates a fairly stable, cool water, oligotrophic environment. However, when focussing in on small scale trends in nannofossil abundances, certain fluctuations, which could be due to minor palaeoenvironmental changes, are observed.

Increased productivity

Biscutum spp., *Discorhadbus* spp., and *Zeugrhabdotus* spp. are considered to reflect changes in productivity. These species thrive in areas of high surface water fertility in low diversity assemblages (Watkins 1989; Erba 1992; Gardin 2001). *Chiastozygus* spp. is also considered to be a high productivity indicator (K. Cooper, pers. comm.). In this study, the high productivity indicators *Biscutum* spp, *Discorhadbus ignotus*, *Placozygus fibuliformis* (as related to *Zeugrhabdotus*, J. Lees, pers. comm.) and *Chiastozygus amphipons* have been grouped together to reinforce their significance (coloured green on Figure 4).

The grouped high productivity indicators demonstrate 2 peaks. The first peak of *P. fibuli-formis* and *Ch. amphipons* occurs between 6616.58' – 6615.92' (within the lower bioturbated interval III). Both *P. fibuliformis* and *Biscutum* spp. peak from 6614.41'-6614.75' (the upper part of laminated interval I and the lower part of the overlying bioturbated interval III. *Chiastozygus amphipons* peaks at 6614.41', within this bioturbated level (Figure 2).

These 2 peaks might be expected to coincide with the laminated zones. However they start to form during the transition from laminated to bioturbated sediments (this is particularly notable on the transition from interval I to interval III).

This apparent offset between the sea-floor anoxic periods and the minor productivity peaks can be explained by a purely physical oceanographic control, whereby alternating 'stormy' and 'calm' periods determine the nature of the sediments. During 'calm' periods, the stratification of the water column allowed pockets of relatively anoxic bottom water to collect in topographic hollows (where M-10X is situated) with weak preservation of organic detritus from pelagic fallout (including coccolith debris) from the surface waters (lneson *et al.* 2004b, this study).

The onset of more stormy conditions destroyed the stratification, mixed the water masses and released the nutrients which had been collecting on the previously quiescent sea floor.

It would be at this point, when the stratification had already broken down and when the nutrients were released back into the water mass as a whole, including the surface waters where the primary producers thrive, that the nannofossils indicative of high primary productivity; *Biscutum* spp., *D. ignotus* & *P. fibuliformis* would start to increase. This could explain why the 'productivity peaks' seen on Figure 4 do not coincide directly with the laminated intervals, but occur slightly later.

Other theories involving levels of high productivity (i.e. lamination formed by high productivity and accumulation rates - Watkins (1989), or the dilution model of Pratt (1981) where periods of greater run-off are associated with a stratified water column and increased organic carbon storage) are ruled out in this area. There is no evidence of high organic carbon levels in the chalk, and palynofacies and sedimentological data show no signs of increased continental run-off (Schiøler 2004, this study).

Palynofacies and dinoflagellate studies do not demonstrate any fluctuation in productivity levels (Schiøler 2004, this study). However, the foraminiferal study shows fluctuations in the planktonic/benthic ratio roughly coinciding with the laminated beds (Lassen & Rasmussen 2004, this study).

Water depth

The palynofacies data of Schiøler (2004, this study) from this cyclic interval do not show any indication of variation in water depth related to the cyclicity. However, abundances of *M. decussata* fluctuate quite markedly (Figure 4). Particularly notable is an influx from 6615.58'-6615.00' (coinciding with an interval of relatively low productivity). This peak is concurrent with a drop in *A. cymbiformis* (at 6615.58'). Both parameters infer a relative rise in water depth at this point. It is also noted that from 6818.41'-6617.17' and from 6614.08'-6613.50' *M. decussata* demonstrate fairly low abundances whilst these intervals show high numbers of *L. cayeuxii* (shallow and cool water indicators). *A. cymbiformis* follow the same trends as *L. cayeuxii* in these intervals, suggesting a relative sea-level shallowing. These intervals coincide with the lower sedimentological unit II (laminated, locally burrowed) and upper unit III (bioturbated, locally laminated) respectively.

Temperature

W. barnesae is thought be a taxon associated with warmer temperatures (Watkins 1992; Lees 2002). A relative increase in this species is seen on Figure 4 over the middle part of the interval, roughly correlating with a decrease in abundance of *L. cay-euxii* (an indicator of cool, fairly shallow waters). This could be inferred to represent a minor warming at the sea surface, although, the seawater in the region was considered at this time to be generally cool.

Several nannofossil species are known to be indicators of cool water and of relatively shallow water.

As previously mentioned, between 6618.41' and 6617.17', there exists an interval of increased *L. cayeuxii* and *A. cymbiformis*. This coincides with reduced numbers of *K. magnificus*. As well as indicating a relative shallowing in sea level, these parameters could suggest a cooling episode. Sedimentologically, this coincides with 'lower interval II'. *L. cayeuxii* and *K. magnificus* are both indicators of high latitude, marginal conditions (Roth 1973; Thierstein 1976; Perch-Nielsen 1979; Pospichal & Wise 1990). Howe-

ver their relative abundance patterns show opposing trends. One explanation for this could be that as they occupy the same niche, they may be in direct competition, with one species being a better temperature or sea-level indicator than the other at that particular time. In addition to this, the interval between 6614.08'– 6612.66' also exhibits a period of relatively high *L. cayeuxii*. As previously, this coincides with a relative increase in *A. cymbiformis*, suggesting a cooler period.

Salinity

The only nannofossil species in this study known to be an indicator of salinity change is *Braarudosphaera bigeloweii*, but as this was only found as a rare occurrence, salinity will not be discussed further here.

Remarks

Generally, the overall nannofossil assemblage patterns and unchanging species richness levels demonstrate a cool, oligotrophic, relatively shallow palaeoenvironment. In more detail, minor fluctuations in certain groups indicate localised, short-lived palaeoecological variation, probably due to changes in nutrients and temperature occurring in tandem with the development and breakdown of watermass stratification controlled by cyclic variation in long-term wind stress. Minor water depth variations can also be inferred from the nanno-fossil data, but other datasets (e.g. palynofacies, micropalaeontology) indicate that this is unlikely to be a significant factor.

Well Interval Scale	Name : M	-10X M-10 19.41' Nann Emm	X cyclicity interv ofossil distribut a Sheldon	al palaeoecology ion (% abundance)					GEUS Copenhagen
		High productivity indicators				Nann	opaleontol	logy	Species richness
			(50mm=100%)						
Depth	Samples (feet)	6 count: High productivity indicators	Markalius inversus Thoracosphaera spp. Cyclagelosphaera reinhardtii Micula decussata	Watznaueria barnesae Ahmuellerella octoradiata Biscutum spp. Chiastozygus amphipons Cribrosphaerella ehrenbergii Eiffellithus turriseiffelii Eiffellithus turriseiffelii	Lucianorhabdus cayeuxii	Vephrolithus frequens Placozygus fibuliformis Dodienschagen crefered	Prediscosphaera ureacea	Effellithus gorkae Octocyclus reinhardtii Retecapsa crenulata Neocrepidolithus coheni Cretarhabdus conicus Munarinus sp. Prediscosphaera spinosa Retecapsa surirella Discorhabdus ignotus Neocrepidolithus neocrassus Octolithus nultiplus Neocrepidolithus ruegenensis Monomarginatus spp. Cylindralithus spp. Braarudosphaera bigelowii Arkhangelskiella cymbiformis	Diversity: Species richness
-	6611.58		32 13						32
6612.0-									
IV 2									
6612.5'-	6612.33						117		
TT -	6612.66	5	.33	86 h h 🖪 h 🖬			-	33 n 33	2916
6613.0			32 32 16	32 2				97 h 32 32 32 65 65 32.	28
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6613.5	6613.50	1 1 AS 2						<u>t 7 133 17 (66 723 533</u>	38) 45
m									
6614.0'-	6614.08							2 2 33 33 33 67 33	36 18
-									
6614.5-	6614.41			86 2 2 2	K —		1-1-		
	6614.75	12	-10	1 33 3 4 4 1 4		68 -	6 4	.33 1 33 33 2 1	20
6615.0-	6615.00	-9	33	33 1 1 1 2 3			63	33 h 33 h 67 h 33	33 21
1	6615.33		25	34 .00 .2 .4				.05 1 1 34 .06 1 34	39 10
6615.5	6615.58		67 2	67 1 2 1				33 h 33 33 h h 67 33 21	23
-									
6616.0	6615.92								
III -	6616.25			33 7 7 8 93 -				1 2 33 33 33	10
6616.5	6616.58	12	67	1 1 1 67	-	33		2 67 1 33 1 2 15	- 22
-									



Figure 4: Detailed section from the Upper Maastrichtian of M-10X showing laminated/bioturbated chalk cycles in relation to nannofossil distribution (% abundance) I: laminated, trace fossil absent (dark blue), II: laminated, with local burrows/diffuse lamination (pale blue), III: bioturbated, local preservation of lamination (orange), IV: bioturbated, lamination absent (yellow)

Correlation of wells

The following table shows the thickness of each palaeoecological unit, allowing comparison between the two wells.

	E-5X			M-10X		
	Base	Тор	Thickness	Base	Тор	Thickness
4	6819.17	?6809.25'	9.92' min	6439.00'	?6433.58	5.42' min
3	6824.83	6819.17	5.66′	6446.50 [′]	6439.00´	7.50′
2	6847.83	6824.83	23.00'	6483.83'	6446.50′	37.33
1C	6920.75	6859.83'	60.92′	6542.58	6483.83´	58.75´
1B	?6975.17'	6920.75'	54.42' min	6601.58'	6542.58'	59.00′
1A	-	-	-	?6655.58'	6601.58'	?54.00' min

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Appendix I: Sample lists

M-10X

List of samples from M-10X (in feet) – aterisked samples are those analysed in the cyclicity level

6434.58	6522.25	6616.58*
6436.33	6525.25	6617.17*
6436.83	6528.92	6617.58*
6438.17	6531.00	6618.00*
6438.83	6533.17	6618.41*
6439.00	6539.92	6618.58*
6439.33	6542.58	6619.00*
6440.50	6546.41	6619.41*
6441.92	6548.92	6623.00
6443.41	6552.25	6626.41
6444.83	6554.83	6629.33
6446.50	6557.58	6631.66
6448.17	6560.75	6634.41
6449.50	6563.41	6637.33
6451.83	6564.66	6641.00
6454.33	6568.25	6644.00
6456.75	6571.17	6647.00
6458.17	6573.66	6648.50
6460.00	6577.08	6652.58
6463.00	6579.83	6655.58
6465.25	6582.58	
6467.66	6586.25	
6472.33	6590.00	
6475.17	6592.00	
6477.00	6598.50	
6481.00	6601.58	
6483.83	6604.92	
6487.25	6608.08	
6489.50	6610.00	
6491.50	6611.58*	
6495.60	6612.33*	
6497.33	6612.66*	
6499.00	6613.08*	
6500.08	6613.50*	
6502.33	6614.08*	
6503.25	6614.41*	
6505.08	6614.58*	

6507.66	6615.00*
6511.50	6615.33*
6514.50	6615.58*
6516.65	6615.92*
6519.41	6616.25*

E-5X

List of samples from E-5X (in feet)

6809.25	6847.83	6919.17
6812.41	6859.83	6920.75
6814.17	6863.33	6923.83
6817.58	6866.25	6926.17
6818.66	6869.33	6928.58
6818.92	6872.66	6932.41
6819.17	6875.33	6935.83
6819.50 (hard chalk)	6877.66	6938.33
6819.50 (soft chalk)	6881.41	6941.17
6820.00	6883.92	6943.25
6821.08	6887.25	6948.92
6823.33	6889.33	6950.41
6824.83	6890.66	6952.92
6826.66	6894.00	6956.83
6827.92	6897.92	6960.17
6830.00	6900.75	6963.17
6833.50	6903.75	6965.17
6836.83	6906.83	6968.58
6839.25	6910.25	6972.17
6841.92	6912.41	6975.17
6845.83	6916.33	

Appendix II: Species Lists

Below is a list of nannofossil species considered in this report to be palaeoenvironmentally significant.

Arkhangelskiella cymbiformis Biscutum dissimilis Biscutum ellipticum Biscutum harrisonii Biscutum magnum Biscutum meleniae Biscutum spp. Chiastozygus amphipons Discorhabdus ignotus Kamptnerius magnificus Lucianorhabdus cayeuxii Micula decussata Placozygus fibuliformis Prediscosphaera stoveri Thoracosphaera spp. Watznaueris barnesae

Below is a list of nannofossil species identified in the interval analysed for cyclicity trends. For a list of all species identified in this report, refer to Sheldon, 2004, this study.

Arkhangelskiella cymbiformis Ahmuellerella octoradiata Biscutum dissimilis **Biscutum ellipticum** Biscutum harrisonii Biscutum magnum Biscutum meleniae Biscutum spp. Braarudosphaera bigeloweii Chiastozygus amphipons Cretarhabdus conicus Cribrosphaerella ehrenbergii Cyclagelosphaera reinhardtii Discorhabdus ignotus Eiffelithus gorkae Eiffelithus turriseiffelii Kamptnerius magnificus Lucianorhabdus cayeuxii Markalius inversus Micula decussata Monomarginatus spp.

Munarinus spp. Neocrepidolithus cohenii Neocrepidolithus cruciatus Neocrepidolithus neocrassus Neocrepidolithus ruegenensis Nephrolithus frequens Octocyclus reinhardtii Octolithus multiplus Placozygus fibuliformis Prediscosphaera cretacea Prediscosphaera spinosa Prediscosphaera stoveri Retecapsa crenulata Retecapsa surirella Thoracosphaera spp. Watznaueria barnesae